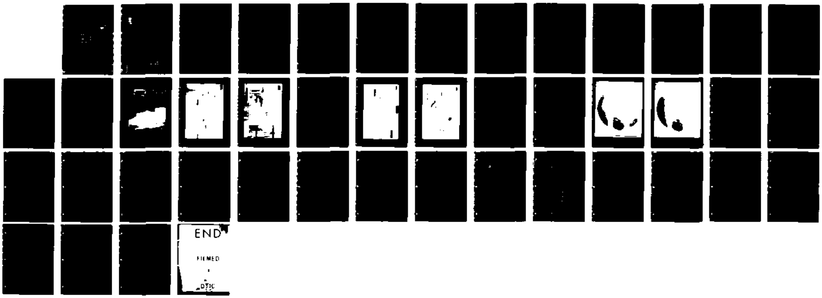
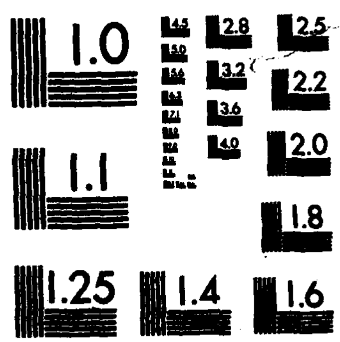
AD-A125 499 SUPERSONIC AND SUBSONIC WIND TUNNEL HEAT-TRANSFER MEASUREMENTS IN THE BAS..(U) ARNOLD ENGINEERING DEVELOPMENT CENTER ARNOLD AFS TN W R HAWKINS ET AL. SEP 82 AEDC-TSR-82-V28 1/1

UNCLASSIFIED F/G 21/8 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

AEDC-TSR-82-V28

SUPERSONIC AND SUBSONIC WIND TUNNEL HEAT-TRANSFER MEASUREMENTS IN THE BASE CAVITY REGION OF THE SHUTTLE SOLID ROCKET BOOSTER DURING SIMULATED REENTRY

W. R. Hawkins and K. W. Nutt

Calspan Field Services, Inc.

September 1982

Final Report for Period August 16-20, 1982

Approved for public release; distribution unlimited.

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

NOTICES
When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.
References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

APPROVAL STATEMENT

This report has been reviewed and approved.

J. T. Best

J. T. BEST
Aeronautical Systems Branch
Deputy for Operations

Approved for publication:

FOR THE COMMANDER

J M Rampy

JOHN M. RAMPY, Director
Aerospace Flight Dynamics Testing
Deputy for Operations

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AEDC-TSR-82-V28	2. GOVT ACCESSION NO. AD-A125499	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SUPERSONIC AND SUBSONIC WIND TUNNEL HEAT-TRANSFER MEASUREMENTS IN THE BASE CAVITY REGION OF THE SHUTTLE SOLID ROCKET BOOSTER DURING SIMULATED REENTRY		5. TYPE OF REPORT & PERIOD COVERED Final Report August 16-20, 1982 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W. R. Hawkins and K. W. Nutt, Calspan Field Services, Inc.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center Air Force Systems Command Arnold Air Force Station, TN 37389		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element - 921E02
11. CONTROLLING OFFICE NAME AND ADDRESS NASA/MSFC ED-33 Huntsville, AL 35812		12. REPORT DATE September 1982 13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in Defense Technical Information Center (DTIC).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

wind tunnel testing
space shuttle
solid rocket booster
reentry heating
cavity heating

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tests were conducted on the aft section of the Space Shuttle Solid Rocket Booster at Mach numbers 3.75 and 0.5 at selected angles of attack from 90-180 deg simulating reentry attitudes. The tests were conducted in the AEDC Supersonic Wind Tunnel A to obtain heat-transfer coefficients in the base cavity region.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

APPENDIXES

NOMENCLATURE

A0	Intercept of linear curve fit (see Eq. 7)
A1	Slope of linear curve fit (see Eq. 8)
ALPB1	Model sting prebend angle, deg (see Fig. 4)
ALPB2	Model adaptor prebend angle, deg (see Fig. 4)
ALPHA	Model angle of attack, deg (see Fig. 4)
ALPI	Indicated sector pitch angle, deg
C1	Gardon gage calibration factor measured at 530°R, Btu/ft^2-sec/mv
C2	Temperature corrected Gardon gage calibration factor, Btu/ft^2-sec/mv (see Eq. 1)
CONFIGURATION	Model configuration designation (see Fig. 5)
DEL	Angle between cylinder local stagnation line and gage or pressure tap
E	Gardon gage output, mv
H-BG, HBG	Reference heat-transfer coefficient on a yawed cylinder of radius 2.19 in. as determined by the Beckwith-Gallagher Method (see Appendix V, Eq. 1) Btu/ft^2-sec-°R
H(TAW)	Heat-transfer coefficient determined from curve-fit of measured heat-flux and wall temperature, Btu/ft^2-sec-°R (see Eq. 8)
H(TT)	Heat-transfer coefficient based on TT, QDOT/(TT-TW), Btu/ft^2-sec-°R
GAGE NUMBER	Gage number designation (see Table 3)
KG	Gardon gage temperature calibration factor, °R/mv
LAMDA	Angular complement of ALPHA, deg |ALPHA-90|
M, MACH NUMBER	Free-stream Mach number
MU, Mu	Dynamic viscosity based on free-stream temperature, lbf-sec/ft^2
n	Number of points used for linear least-squares curve fit of QDOT versus TW
P	Free-stream static pressure, psia
PHI	Model roll angle, deg
PM	Measured model pressure, psia
PSKT	Average of the four aft skirt measured internal pressures, psia
PT	Tunnel stilling chamber pressure, psia

PT2	Total pressure downstream of a normal shock, psia
Q	Free-stream dynamic pressure, psia
QDOT	Heat transfer rate, Btu/ft^2-sec
R2	Linear regression coefficient
RE	Free-stream Reynolds number, ft^{-1}
RHO	Free-stream density, lbm/ft^3
RUN	Data set identification number
ST(TAW)	Computed Stanton number based on TAW, assumes specific heat of air constant, $ST(TAW) = \frac{H(TAW)}{(.24)(RHO)(V)}$
T	Free-stream static temperature, °R
TAP NUMBER	Pressure orifice identification number
TAW	Computed adiabatic wall temperature at each gage location from extrapolation of curve-fit to zero heat flux, °R (see Fig. 8)
TE	Static temperature at boundary-layer edge, °R (see Appendix V, Eq. 4)
TGDEL	Temperature differential between the center and the edge of the Gardon gage disc, °R
TGE	Gardon gage edge temperature, °R
THB	Angular location of model instrumentation measured from + Z in the model fixed coordinate system (see Fig. 7)
THIGH	Highest temperature for which the heating rate versus TW/TT curve was fit, °R
TLOW	Lowest temperature for which the heating rate versus TW/TT curve was fit, °R
TT	Tunnel stilling chamber temperature, °R or °F
TW	Gage surface temperature, °R (see Eq. 3)
V	Free-stream velocity, ft/sec
Y,Z	Orthogonal fixed body axis system directions (see Fig. 7)

1.0 INTRODUCTION

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). under Program Element 921E02, Control Number 9E02, at the request of National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Alabama, for Remtech, Inc., Huntsville, Alabama. The NASA project managers were Ed Brewer and Peter Sulyma and the Remtech project engineers were Leroy Hair and Carl Engel. The results were obtained by Calspan Field Services, Inc./AEDC Division, operating contractor for the Aerospace Flight Dynamics testing effort at the AEDC, AFSC, Arnold Air Force Station, Tennessee. The tests were performed in the Supersonic Wind Tunnel A in the von Karman Gas Dynamics Facility during the period from August 16, 1982 through August 20, 1982, under AEDC Project Number C742VA, (Calspan Project Number V41A-1R).

The primary objective of this test was to determine the internal heating environment on the shuttle solid rocket booster (SRB) skirt base cavity region during simulated reentry conditions.

Data were obtained at Mach numbers 3.75 and 0.5 on a 3-percent scale SRB model at free-stream unit Reynolds numbers of 4.2×10^6 and 3.4×10^6, respectively. Runs were conducted at selected angles of attack and roll angles both with and without the nozzle extension.

To increase the temperature difference between the model surface and the recovery temperature, the model was cooled prior to injection during the supersonic phase using the Tunnel A vortex cooling system. The tunnel was operated with the maximum stagnation temperature available (280°F). During the subsonic phase the direction of heat transfer was reversed to take advantage of an increased driving potential, |TT-TW|. The Tunnel A auxiliary mass flow system was used to heat the model to approximately 280°F prior to injection. The tunnel was operated at a stagnation temperature of nominally 100°F.

A summary of the test data transmitted to the sponsor (NASA/MSFC) and the user (REMTECH) is presented in Table 1. Inquiries to obtain copies of the test data should be directed to NASA-MSFC, ED33, Huntsville, Alabama 35812. A microfilm record of the final tabulated data has been retained at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

Tunnel A (Fig. 1) is a continuous, closed-circuit, variable density wind tunnel with an automatically driven flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel normal operating range is from Mach 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R at Mach number 6.

Minimum operating pressures range from about one-tenth to one-twentieth of the maximum at each Mach number. The tunnel is equipped with a model injection system which allows removal of the model from the test section while the tunnel remains in operation.

Although primarily a supersonic tunnel, Tunnel A can also be operated at subsonic Mach numbers to 0.8 by reducing the diffuser area until choking occurs at this point. The stagnation pressure for the present test was approximately 17 psia. A description of the tunnel and airflow calibration information may be found in the Test Facilities Handbook, Ref. 1.

2.2 TEST HARDWARE

Figure 2 is a photograph of the 3-percent scale model of the aft 40 percent of the SRB installed in the Tunnel A test section. Figure 3 shows the SRB model and the heating/cooling manifold installed in the Tunnel A tank. Figure 4 is the tunnel installation sketch showing the location of the sting prebend angles. The model was constructed of 17-4 stainless steel and supplied to AEDC by NASA/MSFC. The heat-transfer gages were installed at the AEDC. Three configurations were tested. These consisted of the short nozzle, the long nozzle and the short nozzle with the Nevins barrier (see Fig. 5). The intent of the Nevins barrier is to reduce heating in the skirt cavity during reentry.

2.3 TEST INSTRUMENTATION

The measuring devices, recording devices, and calibration methods used for all measured parameters are listed in Table 2a along with the estimated measurement uncertainties. Heat-transfer rate measurements were obtained with thermopile Gardon gages which were supplied and calibrated by the AEDC. The thermopile gage utilizes vapor-deposited layers of antimony and bismuth to form a thermopile on the back surface of the sensing foil. Gage sizes of 1/4 in. and 1/8 in. with sensing foil thicknesses of 0.01 in. and 0.005 in., respectively, were used. The gages were instrumented with Iron-Constantan thermocouples which provided the gage edge temperature measurement. Gage edge temperatures together with the thermopile output were used to determine the gage surface temperatures and corresponding gage heat-transfer rate. These data were then used to compute the local heat-transfer coefficient. A total of 32 Gardon® gages were installed in the model. A photograph showing the general gage arrangement for the short nozzle configuration is shown in Fig. 6. A sketch showing the general arrangement of the model instrumentation is presented in Fig. 7 and body locations are shown in Table 3.

Surface pressure on the model and the tunnel nozzle wall static were measured with the standard Tunnel A pressure system. The system is equipped with 15-psid, Bell and Howell transducers which are referenced to a near vacuum.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

A summary of the nominal test conditions at each Mach number is given below.

M	PT, psia	TT, °F	P, psia	RE x 10^{-6}/ft
3.75	64	280	0.6	4.2
0.5	17	100	14.4	3.4

A test summary showing all configurations tested and the variables for each is presented in Table 4.

3.2 TEST PROCEDURES

In the AEDC continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. A given injection cycle is termed a run, and all the data are identified in the data tabulations by a run number.

The test procedure was as follows:

1. During the supersonic test phase (M = 3.75) the model was cooled with an air distribution manifold (see Fig. 3) ensuring that the temperature was approximately 50°F and all gage edge thermocouples were within ±20°F of each other as judged by a video display of the temperature data.

2. The model was then injected at the desired test attitude, taking about 13 sec to reach the tunnel centerline and another 6 sec to travel to the forward test section.

3. At lift-off, a single loop of data was recorded followed by an 11-sec delay before data taking was resumed at approximately two-sec intervals until the model reached the full forward position. Subsequent single loops of data were taken at controlled time intervals as the measured heating rate decreased with time. (Nominally 90 sec).

4. The model was then retracted and the data recording was terminated. After each test run the model was cooled and prepared for a subsequent injection.

5. During the subsonic test phase ($M = 0.50$) the test procedure was identical except that the model was heated using the auxiliary mass flow system and the manifold distribution system described for the supersonic phase. The model was heated to approximately 280°F and the total temperature in the tunnel was maintained at nominally 100°F.

3.3 DATA REDUCTION

All free-stream parameters were computed assuming a perfect gas isentropic expansion from the tunnel stilling chamber and utilizing the measured pressure and temperature in the stilling chamber and the calibrated Mach number in the test section. Subsonically, the Mach number was determined by the ratio of tunnel stilling chamber and test section static pressure.

The thermopile Gardon gages used in the model are direct reading heat-flux transducers whose output may be converted to heating rate by means of a scale factor (see Table 5). The thermopile Gardon gage scale factor has been found to be a function of temperature, and therefore must be corrected for gage temperature changes according to the following equation.

$$C2 = C1[4.72878 - (2.83765 \times 10^{-2})(TGE) + (7.82707 \times 10^{-5})(TGE)^2 - (9.44869 \times 10^{-8})(TGE)^3 + (4.30151 \times 10^{-11})(TGE)^4] \quad (1)$$

The heat flux to the thermopile gage can be calculated for any data point by the following equation:

$$QDOT = (E)(C2) \quad (2)$$

The gage wall temperature is given by

$$TW = TGE + 0.75\ TGDEL \quad (3)$$

where the factor 0.75 represents the average, or integrated, value across the gage and

$$TGDEL = (KG)(E) \quad (4)$$

The "optional" Gardon gage data reduction procedure was used to compute the heat-transfer coefficient. This technique provides a method for extrapolating to adiabatic wall temperature. This is important in Tunnel A where the difference between the model wall temperature and the adiabatic wall temperature is small. This small temperature difference causes the calculation of the heat-transfer coefficient to be sensitive to deviations from the actual adiabatic wall temperature. The special data reduction procedure is based on the concept that

$$H(TAW) = \frac{QDOT}{TAW - TW} \quad (5)$$

where H(TAW) is assumed to be constant. Rearranging Equation (5) gives

$$QDOT = [H(TAW)][TAW] - [H(TAW)][TW] \tag{6}$$

where [H(TAW)][TAW] is a constant. Therefore, Equation (6) can be written in the form of a straight line

$$QDOT = A0 + A1(TW) \tag{7}$$

Since A0 and A1 are constant, a comparison of Equations (6) and (7) gives

$$H(TAW) = -A1 \tag{8}$$

Setting QDOT = 0 in Equation (7) and solving for TW leads to the following relationship:

$$TAW = \frac{-A0}{A1} \tag{9}$$

The actual steps in the data reduction procedure are to obtain a linear curve fit of QDOT versus TW for each gage (a typical plot is shown in Fig. 8) and evaluate A0 and A1 in Equation (7). The quality of the curve fit is verified by examining the plotted data on a graphics display terminal. When the curve fit has been verified, the heat transfer coefficient can be calculated from Equation (8) and the adiabatic wall temperature can be determined from Equation (9). The value of TAW is checked to see if it is within the following range:

$$0.8 \leq \frac{TAW}{TT} \leq 1.01 \tag{10}$$

If Equation (10) is not satisfied, an asterisk is printed next to the value of TAW in the tabulated data.

The Stanton number based on adiabatic wall temperature may then be calculated by assuming a constant specific heat for air by:

$$ST(TAW) = \frac{H(TAW)}{(.24)(RHO)(V)} \tag{11}$$

Appendix V contains a theoretical method (Ref. 2) for computing the stagnation-line heat-flux to a yawed cylinder. This method was used as the reference value for the experimentally derived heating coefficients. Representative plots are shown in Appendix IV.

A linear regression coefficient (R2) was used to indicate the quality of curve fit for the QDOT versus TW plots where

$$QDOT = A0 + (A1)(TW)$$

The linear regression coefficient is defined by:

$$R2 = \frac{\left[\sum(QDOT)_i(TW)_i - \frac{\sum(QDOT)_i \sum(TW)_i}{n}\right]^2}{\left[\sum(TW)_i^2 - \frac{(\sum(TW)_i^2}{n}\right]\left[\sum(QDOT)_i^2 - \frac{(\sum(QDOT)_i^2}{n}\right]} \qquad (12)$$

The closer this value approaches 1.0, the better the quality of curve fit indicated.

In certain instances of very low heating, a valid linear curve fit could not be determined using the "optional" Gardon gage technique. In these cases, the "standard" Gardon gage heat-transfer coefficient was calculated by averaging 5 loops of measured QDOT and gage-edge temperature after full-forward was attained. In this case:

$$H(TAW) = H(TT) = \frac{QDOT}{TT-TW}\ ,\ Btu/ft^2\text{-sec-}^\circ R$$

These gages are annotated with an A in the Tabulated Data.

3.4 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as:

$$U = \pm(B + t_{95}S) \qquad (13)$$

where B is the bias limit, S is the sample standard deviation and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 2a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 3 and the results are given in Table 2b.

4.0 DATA PACKAGE PRESENTATION

Sample data tabulations are presented in Appendix III. In addition to the tunnel conditions, the measured adiabatic wall temperatures (TAW) and calculated heating coefficients H(TAW) are tabulated for each run. The model pressure data are included for each run to aid in evaluating the calculated heating coefficients. In addition, shadowgraphs were taken of each run to aid in the flow-field determination. Representative examples of these data are presented in Fig. 9.

During model testing some gages became inoperative. These gages are labeled as inoperative on the tabulated data.

REFERENCES

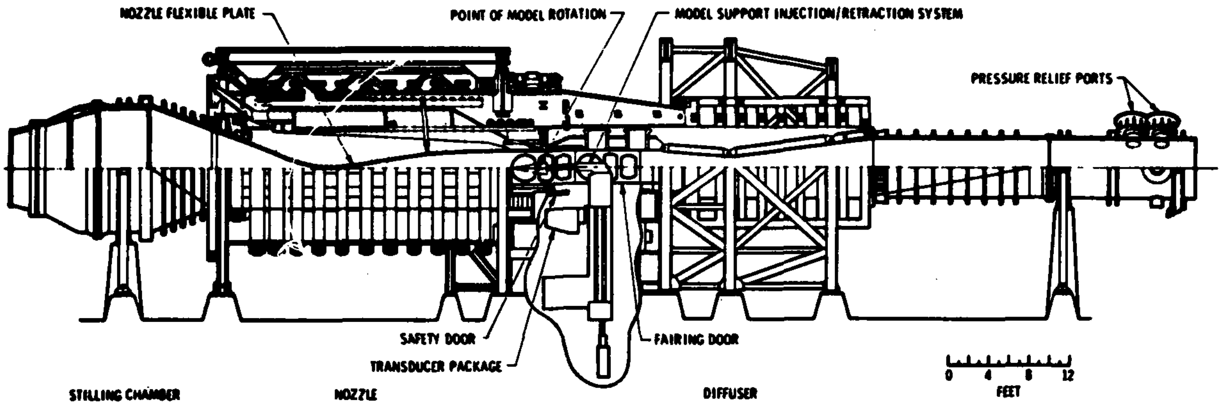
1. Test Facilities Handbook (Eleventh Edition). "Von Karman Gas Dynamics Facility Vol. 3". Arnold Engineering Development Center, April 1981.

2. Beckwith, I. E. and Gallagher, J. J. "Local Heat Transfer and Recovery Temperatures on a Yawed Cylinder at a Mach Number of 4.15 and High Reynolds Numbers," NASA TR R-104, 1961.

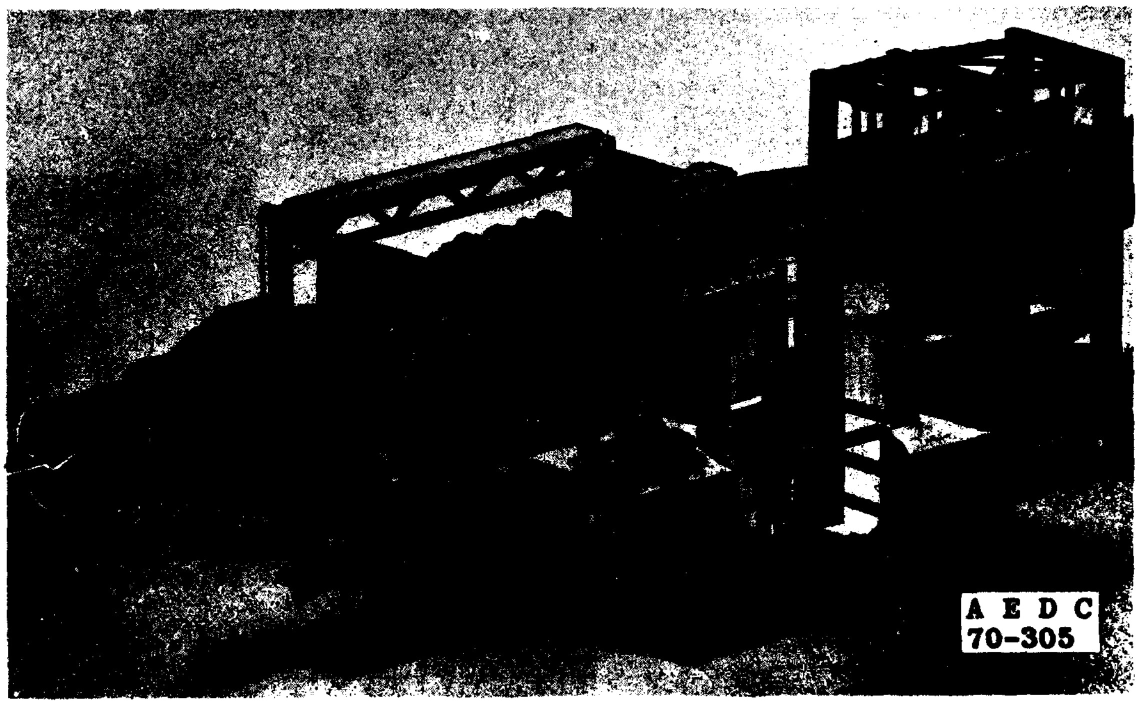
3. Abernethy, R. B., Thompson, J. W., et al. "Handbook of Uncertainty in Gas Turbine Measurements," AEDC-TR-73-5 (AD755356), February 1973.

APPENDIX I

ILLUSTRATIONS



a. Tunnel assembly



b. Tunnel test section
Fig. 1 Tunnel A

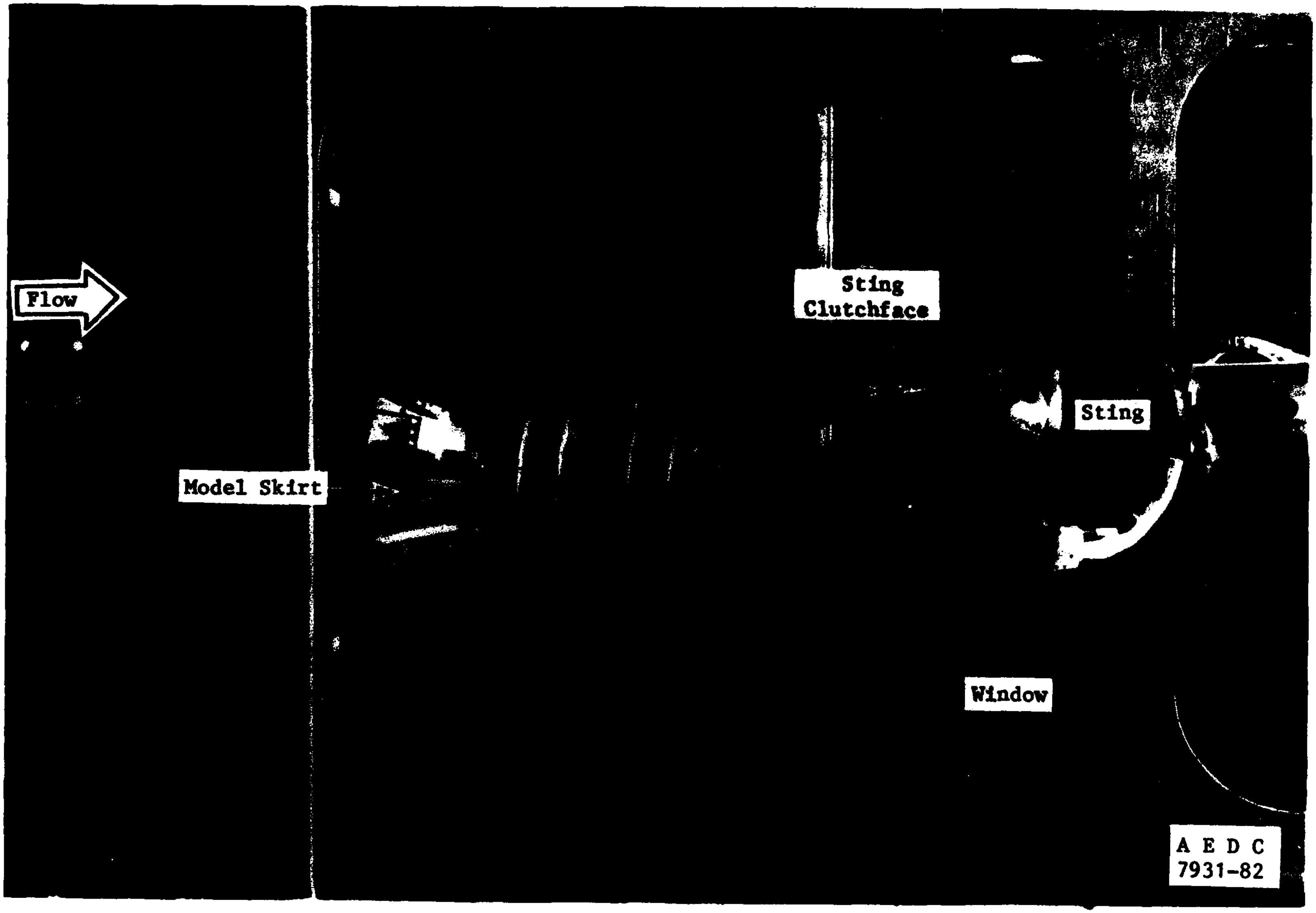


Figure 2. Shuttle Solid Rocket Booster Model in Tunnel A

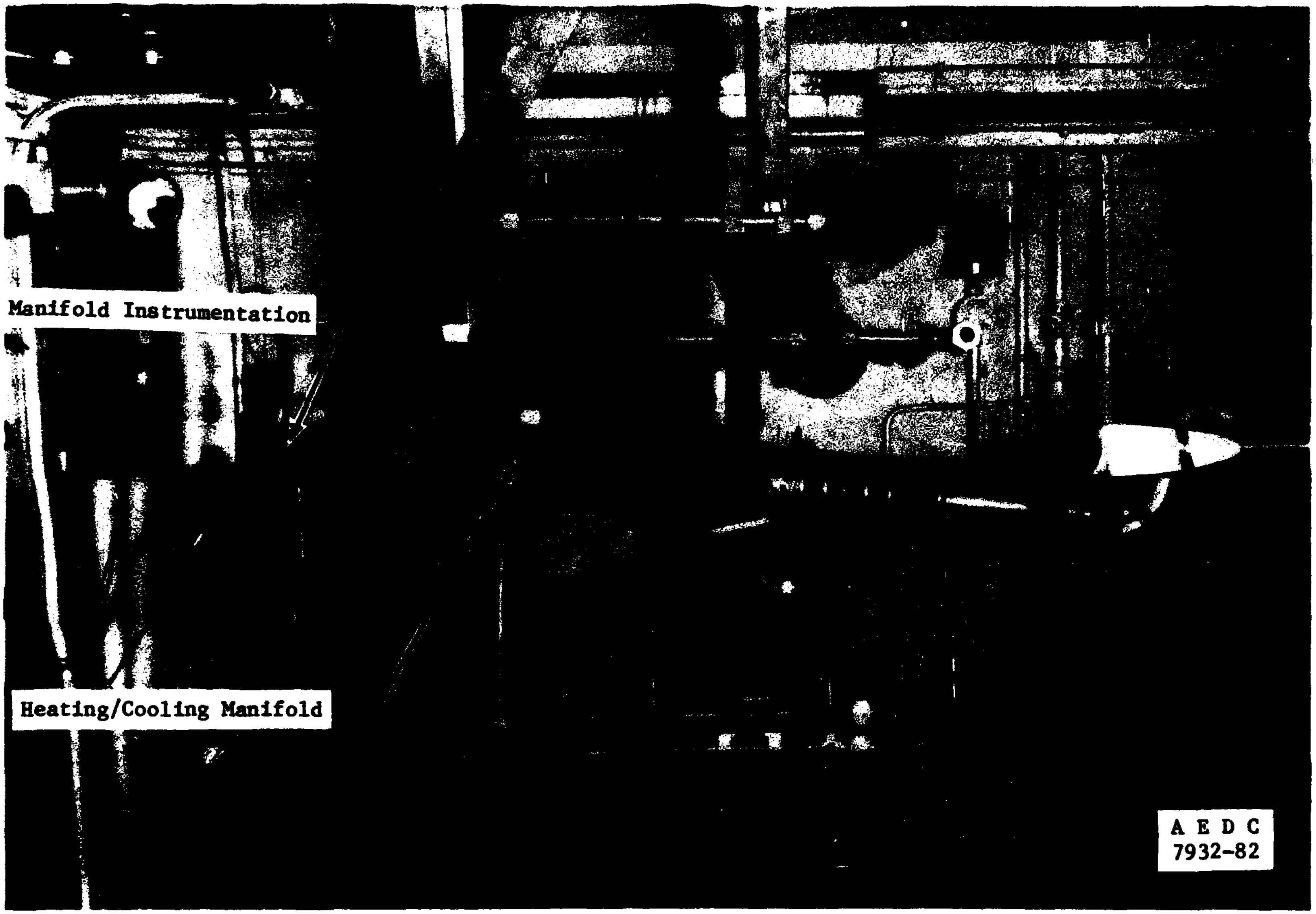


Figure 3. Installation Photograph in Tunnel A Tank

40—INCH SUPERSONIC TUNNEL A

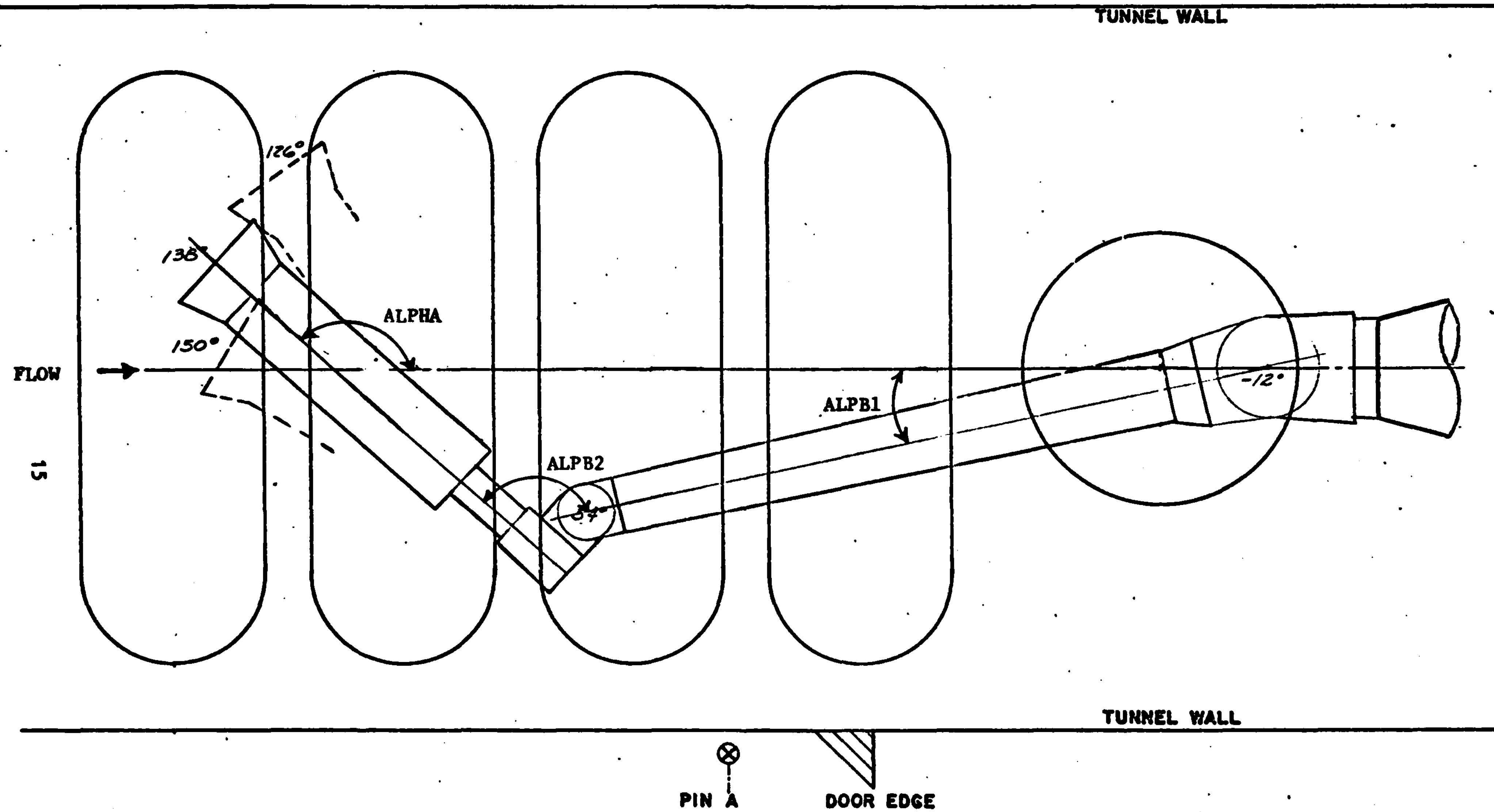


Figure 4. Tunnel Installation Sketch

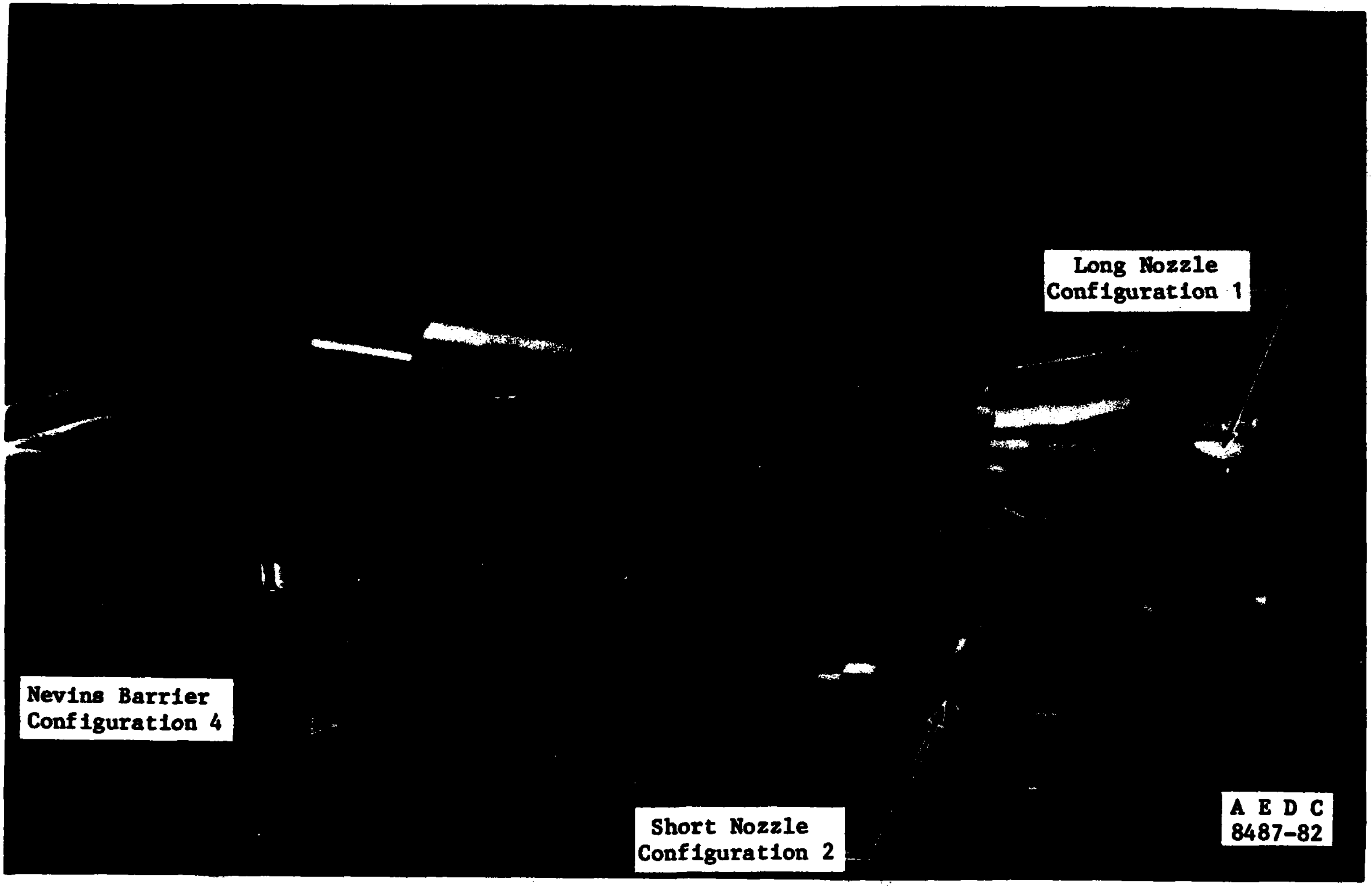


Figure 5. Model Configurations Tested

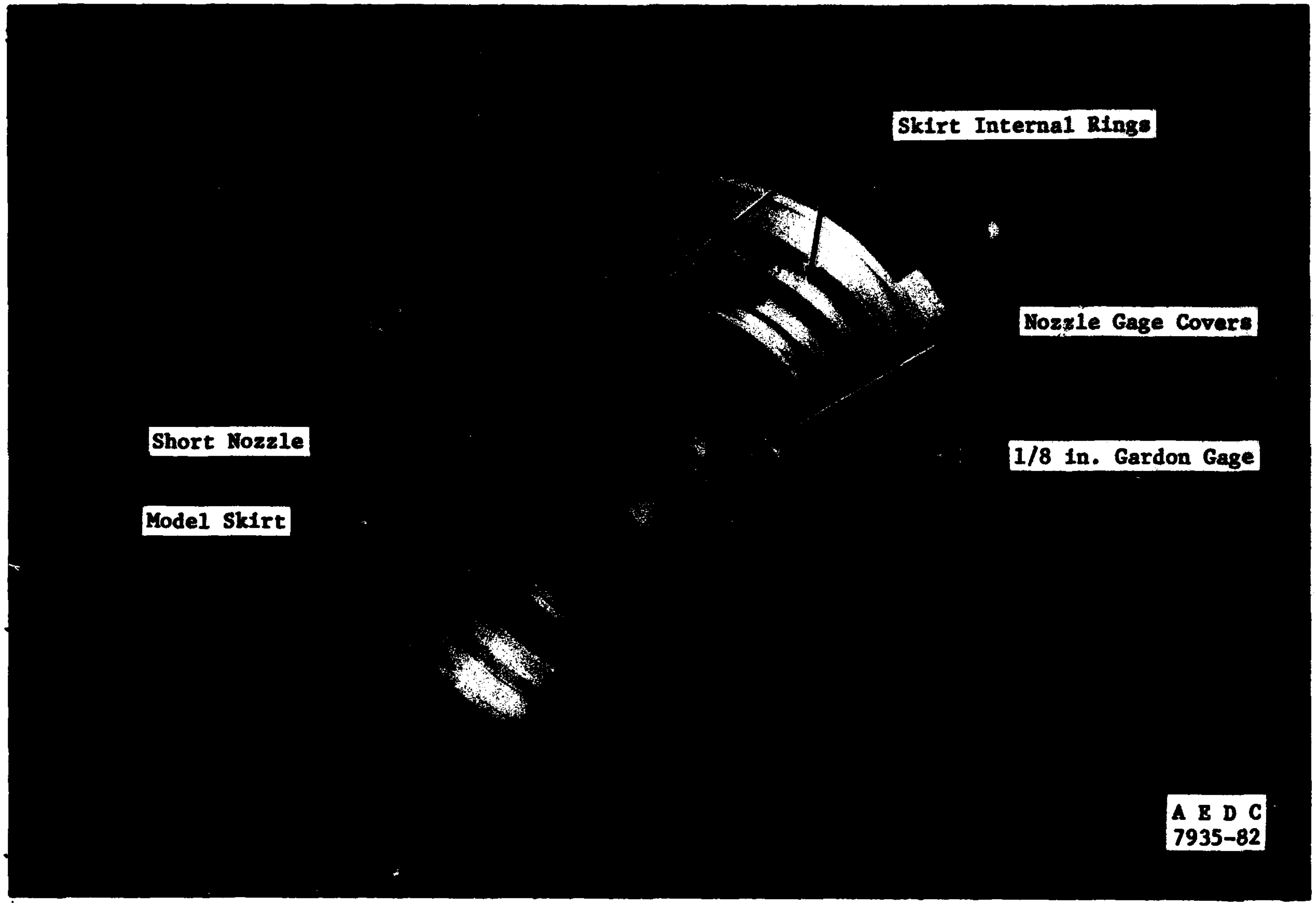
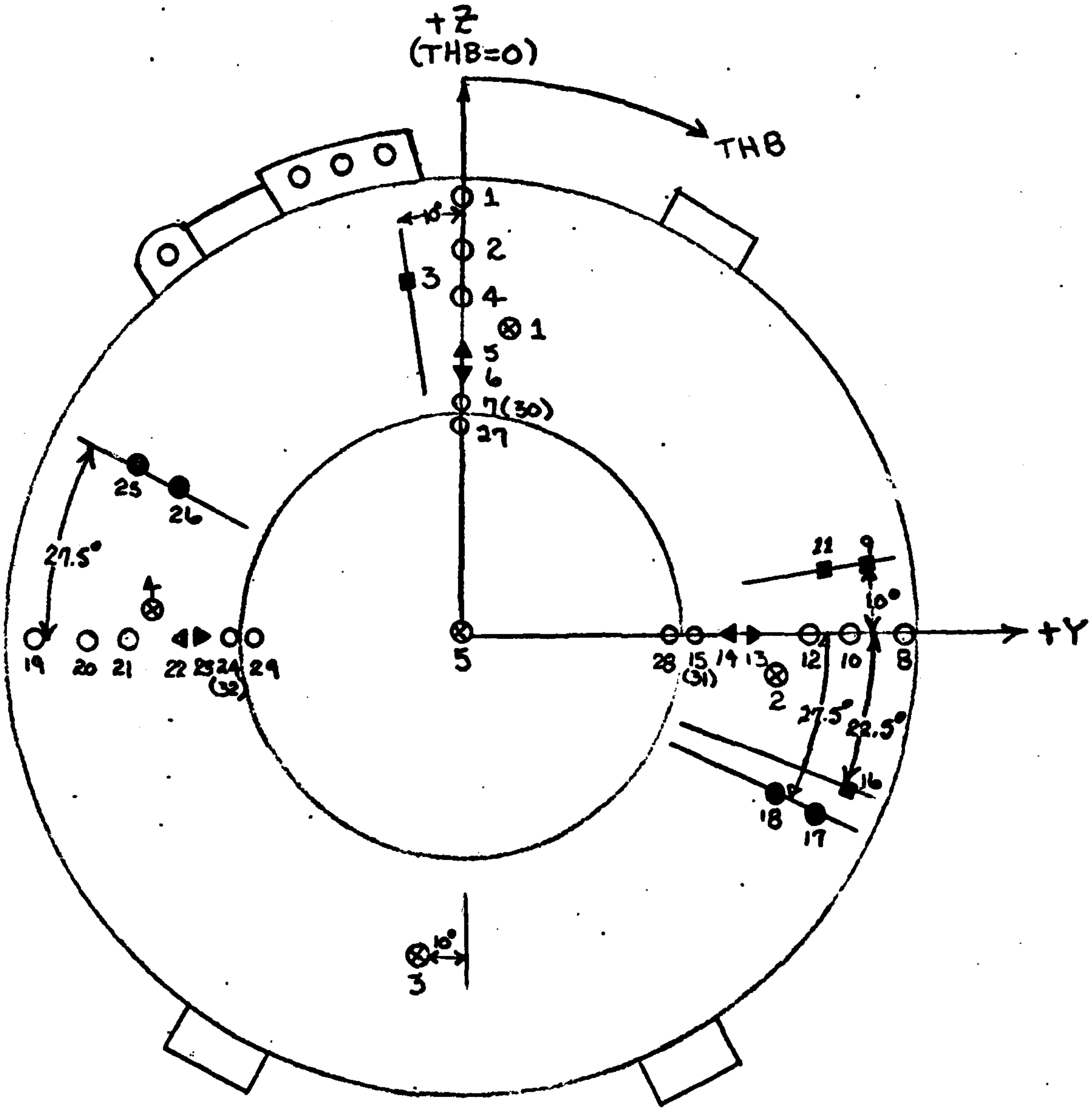


Figure 6. Photograph of Short Nozzle Configuration Showing General Gage Arrangement



Gardon® Gages

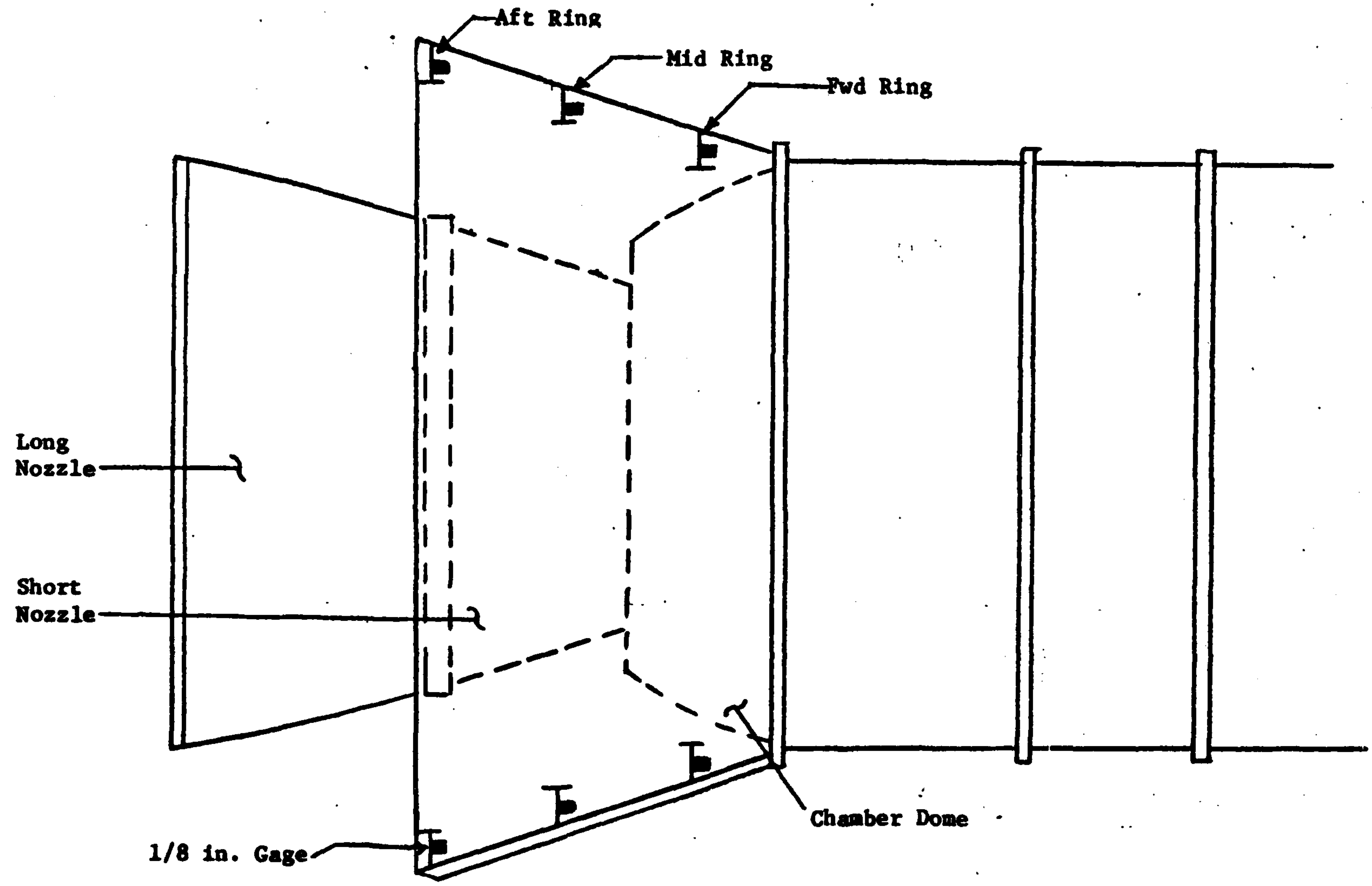
- ○ Facing aft on rings
- ○ On nozzle surface
- ▶ Chamber Dome
- ■ Internal Skin
- ● Facing fwd on rings

Pressure

- ⊗ Chamber Dome

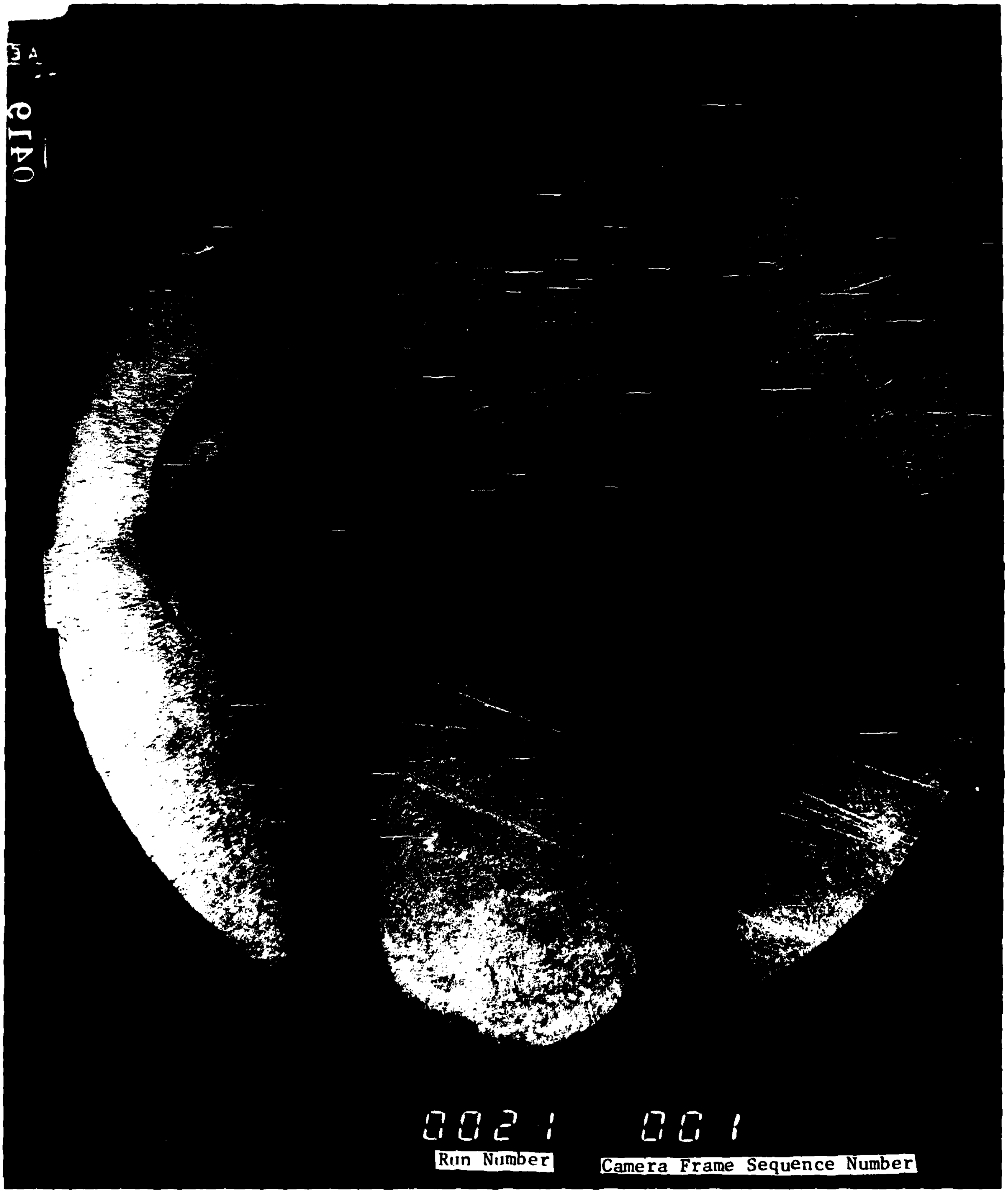
a. View Looking Aft

Figure 7. Model Instrumentation Sketch



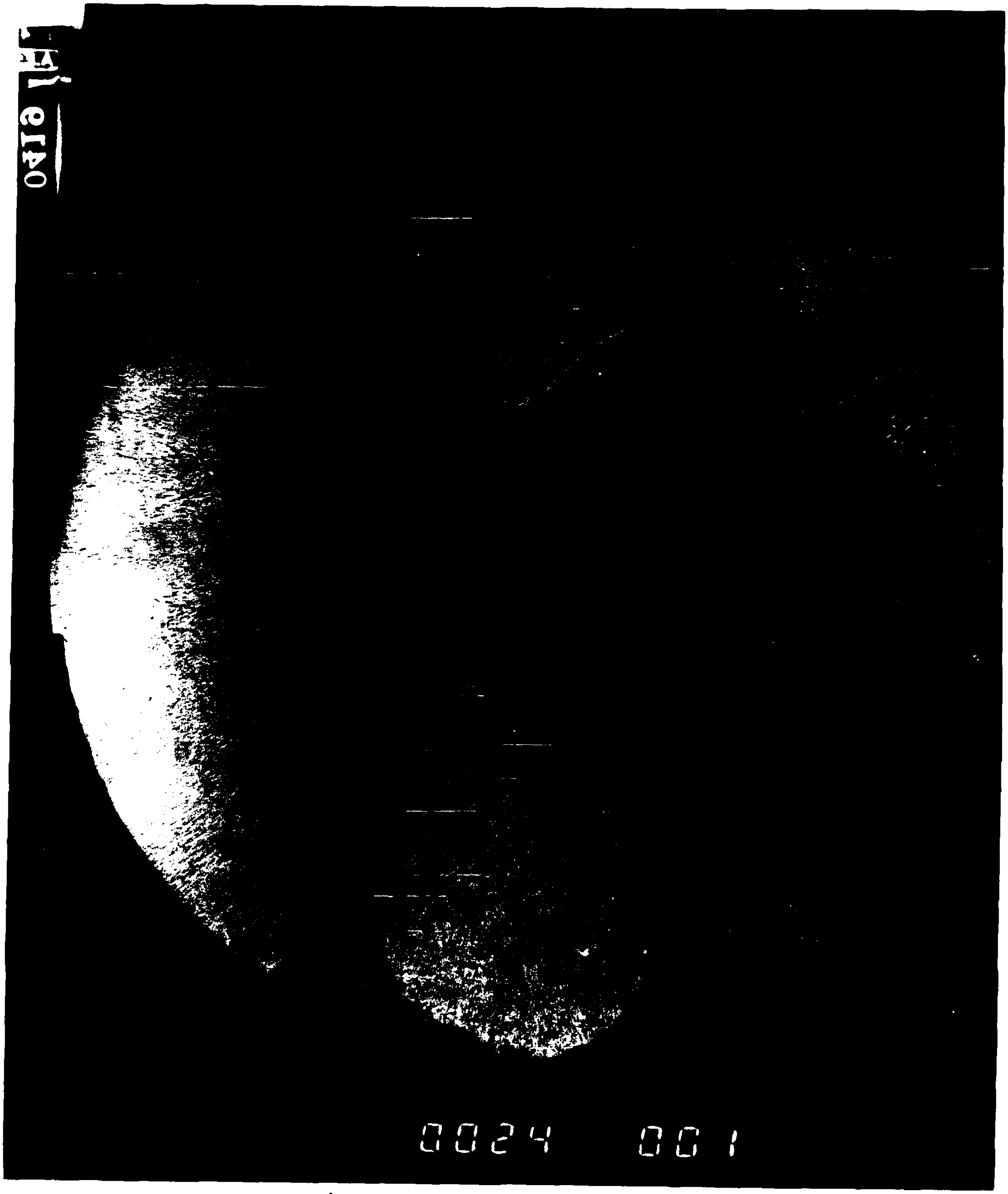
b. Side View

Figure 7. Concluded



a. M = 3.75, ALPHA = 168

Figure 9. Shadowgraph Depicting Model Flow Field



b. M = 3.75, ALPHA = 138

Figure 9. Concluded

APPENDIX II

TABLES

TABLE 1. Data Transmittal Summary

The following items were transmitted to the User and Sponsor:

User	Sponsor
Leroy M. Hair Remtech, Inc. 2603 Artie St. Suite 21 Huntsville, AL 35805	Peter Sulyma ED-33 NASA/MSFC Huntsville, AL 35812

Item	No. of Copies	No. of Copies
Test Summary Report	3	3
Final Data Package	2	2
70 mm Shadowgraph Stills rolls 0418, 0419, 0421	1 contact print 1 positive transparency	1 contact print 1 duplicate negative
Specimen Pretest Photos	1 each 8x10 prints	1 each 8x10 prints
Installation Photos	1 each 8x10 prints	1 each 8x10 prints

TABLE 2. ESTIMATED UNCERTAINTIES

a. Basic Measurements

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index ±(S) Percent of Reading	Precision Index ±(S) Unit of Measurement	Precision Index ±(S) Degree of Freedom	Bias ±(B) Percent of Reading	Bias ±(B) Unit of Measurement	Uncertainty $\pm(B + t_{95}S)$ Percent of Reading	Uncertainty $\pm(B + t_{95}S)$ Unit of Measurement	Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
PT, psia		0.007	>30	0.2		±(0.2% + 0.014)		60	Bell and Howell force balance pressure transducer	Digital Data acquisition system analog-to-digital converter	In-place application of multiple pressure levels measured with a pressure measuring device calibrated in the Standards Laboratory
REFERENCE PRESSURE (PREF), microns		25	>30	10		±(10% + 50)		1000	Hastings vacuum gage		Comparison to facility reference gage
TIME CODE GENERATOR sec		5×10^{-4}	>30	(Runtime(sec)$\times 5\times10^{-6}$) ±		[(Runtime(sec)$\times 5\times10^{-6}$)] + 10^{-3}		0 to 365 days	Systron Donner time code generator	Digital data acquisition system	Instrument lab calibration against Bureau of Standards
TT, °F		1	>30	10^{-3}	2		4	0-300	Chromel®-Alumel® thermocouple	Doric temperature instrument digital multiplexer	Thermocouple verification of NBS conformity/voltage substitution calib.
TV, °F(Fe-CN)		1	>30		2		4	50 to 300	Fe-CN thermocouple	Low-level multiplex system	Voltage substitution calibration, secondary standard
RHO, lbm/in.^{3}	0+			1.0		1.0			Potentiometer	Digital data acquisition system analog-to-digital converter	Heidenhain rotary encoder ROD 700 Resolution: 0.0006° Overall accuracy: 0.001°
ALPI, deg		0.035	>30		0+		0.06	±15			

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.

+ Assumed to be zero

GC-120 (2/81)

TABLE 2. Concluded

b. Calculated Parameters

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading	Precision Index (S) Unit of Measurement	Precision Index (S) Degree of Freedom	Bias (B) Percent of Reading	Bias (B) Unit of Measurement	Uncertainty $\pm(B + t_{95}S)$ Percent of Reading	Uncertainty $\pm(B + t_{95}S)$ Unit of Measurement	Range
PT2,psia	0.69		30	0.20		1.58		All
Q,psia	0.67		30	0.20		1.54		All
RE	0.49		30	0.48		1.46		All
M		0.008 0.01	30 30		0+ 0+		0.016 0.02	3.75 0.5
ALPHA,deg		1			0+		2	All
QDOT,BTU/ft^2-sec	2.0		30	4.0		8.0		1-3

*Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

TABLE 3. Model Instrumentation

GAGE NO.	THB (deg)	LOCATION
1	0	Aft ring facing aft
2	0	Mid ring facing aft
3	350	Mid bay on skin
4	0	Fwd ring facing aft
5	2.5	Chamber dome side
6	357.5	Chamber dome facing aft
*7 (30)	0	Nozzle
8	90	Aft ring facing aft
9	80	Aft bay on skin
10	90	Mid ring facing aft
11	80	Mid bay on skin
12	90	Fwd ring facing aft
13	92.5	Chamber dome side
14	87.5	Chamber dome facing aft
*15 (31)	90	Nozzle
16	112.5	Aft bay on skin
17	117.5	Mid ring facing fwd
18	117.5	Fwd ring facing fwd
19	270	Aft ring facing aft
20	270	Mid ring facing aft
21	270	Fwd ring facing aft
22	272.5	Chamber dome side
23	267.5	Chamber dome facing aft
*24 (32)	270	Nozzle
25	297.5	Mid ring facing fwd
26	297.5	Fwd ring facing fwd
*27	0	Nozzle extension
*28	70	↓
*29	270	↓

PRESSURE GAGE NO.	THB (deg)	LOCATION
1	10	Chamber dome facing aft
2	100	↓
3	190	↓
4	280	↓
5	0	Inside nozzle cavity

* Denotes long nozzle gages

( ) Denotes short nozzle gages

TABLE 4. Test Summary

Runs 1-39 M = 3.75				Runs 40-68 M = 0.50			
RUN NO.	CONFIGURATION	ALPHA	PHI	RUN NO.	CONFIGURATION	ALPHA	PHI
1	2	180	90	35	1	138	300
2		168		36		126	
3		162		37		114	
4		168	270	38		180	
5		150		39		162	
6		138		40		174	270
7		126		42		162	
8		114		43		174	
9		90		44		168	
10		150	300	45		150	
11		138		46		138	
12		126		47		126	
13		168		48		114	
14		162		49		90	
15		162	330	50		162	330
16		150		51		150	
17		126		52		126	
18	4	162		53		150	300
19	4	180		54		138	
20	1	180	270	55		126	
21		168		56		162	
22		162		57		168	
23		150		58		180	
24		138		59	2	138	270
25		126		60		114	
26		114		61		90	
27		90	330	62		162	
28		150		63		174	
29		126		64		162	330
30		162		65		162	300
31		162	300	66		180	
32		168		67		138	
33		174		68		114	
34		150					

Configuration 1 - Long nozzle

Configuration 2 - Short nozzle

Configuration 3 - Long nozzle with Nevins barrier (not tested)

Configuration 4 - Short nozzle with Nevins barrier

TABLE 5. Heat Gage Calibration Factors

a. Runs 1 - 19

DATA REDUCTION CONSTANTS

GAGE NO.	C1 (BTU/ft^2-sec/mv)	KG (°R/mv)	GAGE DIA (in.)
1	3.03	8.5	0.125
2	1.85	5.2	0.125
3	2.59	7.3	0.125
4	1.86	5.2	0.125
5	2.31	6.5	0.125
6	1.78	5.0	0.125
8	2.38	7.8	0.125
9	0.653	4.4	0.250
10	2.66	7.4	0.125
11	0.921	6.3	0.250
12	2.66	7.4	0.125
13	1.86	5.2	0.125
14	2.90	8.1	0.125
16	0.849	5.8	0.250
17	2.23	6.2	0.125
18	1.95	5.5	0.125
19	1.95	5.5	0.125
20	2.36	6.6	0.125
21	2.04	5.7	0.125
22	1.83	5.1	0.125
23	2.25	6.3	0.125
24	0.817	5.6	0.250
25	2.06	5.8	0.125
26	2.41	6.7	0.125
30	0.647	4.4	0.250
31	0.685	4.7	0.250
32	0.704	4.8	0.250

NOTE: The change in calibration factor for a selected gage resulted from gage replacement during the test.

TABLE 5. Continued

b. Runs 20 - 39

DATA REDUCTION CONSTANTS

GAGE NO.	C1 (BTU/ft^2-sec/mv)	KG (°R/mv)	GAGE DIA (in.)
1	3.03	8.5	0.125
2	3.14	8.8	0.125
3	2.59	7.3	0.125
4	1.86	5.2	0.125
5	2.31	6.5	0.125
6	1.78	5.0	0.125
7	0.669	4.5	0.250
8	2.38	7.8	0.125
9	0.653	4.4	0.250
10	2.66	7.4	0.125
11	0.921	6.3	0.250
12	2.66	7.4	0.125
13	1.86	5.2	0.125
14	2.90	8.1	0.125
15	0.647	4.4	0.250
16	0.849	5.8	0.250
17	2.38	6.7	0.125
18	1.95	5.5	0.125
19	2.45	6.9	0.125
20	2.36	6.6	0.125
21	2.04	5.7	0.125
22	1.83	5.1	0.125
23	3.43	9.6	0.125
24	0.817	5.6	0.250
25	2.06	5.8	0.125
26	2.41	6.7	0.125
27	0.599	4.1	0.250
28	0.784	5.3	0.250
29	0.715	4.9	0.250

TABLE 5. Concluded

c. Runs 40 - 68

DATA REDUCTION CONSTANTS

GAGE NO.	C1 (BTU/ft^2-sec/mv)	KG (°R/mv)	GAGE DIA (in.)
1	3.03	8.5	0.125
2	3.14	8.8	0.125
3	2.59	7.3	0.125
4	3.19	8.9	0.125
5	2.31	6.5	0.125
6	1.78	5.0	0.125
7	1.07	3.6	0.250
8	3.08	8.6	0.125
9	0.653	4.4	0.250
10	2.66	7.4	0.125
11	0.921	6.3	0.250
12	2.66	7.4	0.125
13	1.86	5.2	0.125
14	2.90	8.1	0.125
15	1.18	4.0	0.250
16	0.849	5.8	0.250
17	2.38	6.7	0.125
18	1.95	5.5	0.125
19	2.45	6.9	0.125
20	2.36	6.6	0.125
21	2.63	7.4	0.125
22	1.83	5.1	0.125
23	3.43	9.6	0.125
24	1.10	3.7	0.250
25	2.06	5.8	0.125
26	2.41	6.7	0.125
27	0.533	4.7	0.250
28	1.16	3.9	0.250
29	1.05	3.6	0.250
30	0.284	4.4	0.250
31	0.685	4.7	0.250
32	0.704	4.8	0.250

APPENDIX III

SAMPLE TABULATED DATA

ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/REMTECH SRB INTERNAL HEATING

DATE COMPUTED 23-SEP-82
TIME COMPUTED 12:21:57
DATE RECORDED 10-AUG-82
TIME RECORDED 19: 9:20
PROJECT NUMBER V A 1R

RUN	CONFIGURATION	MACH NUMBER	PT (PSIA)	TT (DEGR)	ALPHA (DEG)	ALPI (DEG)	ALPB1 (DEG)	ALPB2 (DEG)	PHI (DEG)
1	SHORT NOZZLE	3.75	64.11	743.7	180.0	-6.0	0.0	6.0	90.0

T (DEGR)	P (PSIA)	Q (PSIA)	V (FT/SEC)	RHO (LBM/FT3)	MU (LBF-SEC/FT2)	RE (FT-1)	H-BG (BTU/FT2-SEC-R)	PT2 (PSIA)	PSKT (PSIA)
195.1	5.925E-01	5.83	2567.5	8.199E-03	1.570E-07	4.168E+06	4.046E-03	1.101E+01	1.056E+01

GAGE NUMBER	THB (DEG)	DEL (DEG)	TAW (DEGR)	TAW/TT	H(TAW) (BTU/FT2-SEC-R)	ST(TAW)	H(TAW)/ H-BG	H(TAW)/ PT2**.8	H(TAW)/ PSKT**.8	TLOW (DEGR)	THIGH (DEGR)	R2
1	INOPERATIVE											
2	INOPERATIVE											
3	350.0	100.0	746.6	1.0039	1.087E-02	2.152E-03	2.687E+00	1.596E-03	1.649E-03	560.2	690.5	9.886E-01
4	0.0	90.0	743.9	1.0003	1.369E-02	2.711E-03	3.385E+00	2.010E-03	2.077E-03	601.6	705.0	9.959E-01
5	2.5	87.5	729.7	0.9812	1.045E-02	2.068E-03	2.582E+00	1.533E-03	1.585E-03	550.1	657.4	9.819E-01
6	357.5	92.5	756.3	1.0170	1.761E-02	3.485E-03	4.352E+00	2.585E-03	2.671E-03	568.2	671.0	9.916E-01
8	90.0	0.0	706.7	0.9503	1.326E-02	2.624E-03	3.277E+00	1.946E-03	2.011E-03	614.4	706.8	9.958E-01
9	80.0	10.0	740.2	0.9953	1.349E-02	2.671E-03	3.335E+00	1.981E-03	2.047E-03	575.8	697.3	9.978E-01
10	90.0	0.0	731.5	0.9836	1.046E-02	2.071E-03	2.586E+00	1.536E-03	1.587E-03	595.6	708.3	9.957E-01
11	80.0	10.0	757.3	1.0184	1.146E-02	2.269E-03	2.833E+00	1.682E-03	1.739E-03	577.8	707.0	9.887E-01
12	90.0	0.0	740.0	0.9950	1.271E-02	2.516E-03	3.142E+00	1.866E-03	1.928E-03	596.1	691.8	9.907E-01
13	92.5	2.5	776.6	1.0443	6.858E-03	1.358E-03	1.695E+00	1.007E-03	1.040E-03	549.3	641.5	9.709E-01
14	87.5	2.5	718.3	0.9659	1.383E-02	2.738E-03	3.418E+00	2.030E-03	2.098E-03	552.2	632.4	9.768E-01
16	112.5	22.5	739.2	0.9940	8.430E-03	1.669E-03	2.084E+00	1.237E-03	1.279E-03	558.0	682.8	9.863E-01
17	117.5	27.5	742.9	0.9990	1.463E-02	2.897E-03	3.617E+00	2.148E-03	2.220E-03	577.9	697.7	9.908E-01
18	117.5	27.5	744.0	1.0004	7.188E-03	1.423E-03	1.777E+00	1.055E-03	1.090E-03	575.7	682.5	9.859E-01
19	270.0	180.0	735.9	0.9896	2.281E-02	4.516E-03	5.639E+00	3.349E-03	3.461E-03	623.8	733.3	9.985E-01
20	270.0	180.0	744.0	1.0005	2.052E-02	4.062E-03	5.071E+00	3.012E-03	3.112E-03	607.0	729.8	9.962E-01
21	270.0	180.0	724.4	0.9741	2.070E-02	4.097E-03	5.116E+00	3.038E-03	3.140E-03	593.6	711.8	9.974E-01
22A	272.5	177.5	743.7	1.0000	1.102E-02	2.182E-03	2.724E+00	1.618E-03	1.672E-03			
23	INOPERATIVE											
25	297.5	152.5	738.0	0.9924	1.770E-02	3.504E-03	4.376E+00	2.599E-03	2.685E-03	583.4	728.2	9.976E-01
26	297.5	152.5	728.3	0.9793	1.242E-02	2.459E-03	3.070E+00	1.823E-03	1.884E-03	571.0	707.8	9.899E-01
30	INOPERATIVE											
31	90.0	0.0	748.1	1.0059	1.043E-02	2.065E-03	2.579E+00	1.531E-03	1.583E-03	560.0	702.1	9.905E-01
32	270.0	180.0	758.8	1.0204	1.963E-02	3.887E-03	4.853E+00	2.882E-03	2.978E-03	578.0	723.9	9.984E-01

ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/REMTECH SRB INTERNAL HEATING

DATE COMPUTED 23-SEP-82
TIME COMPUTED 12:21:59
DATE RECORDED 16-AUG-82
TIME RECORDED 19: 9:20
PROJECT NUMBER V A 1R

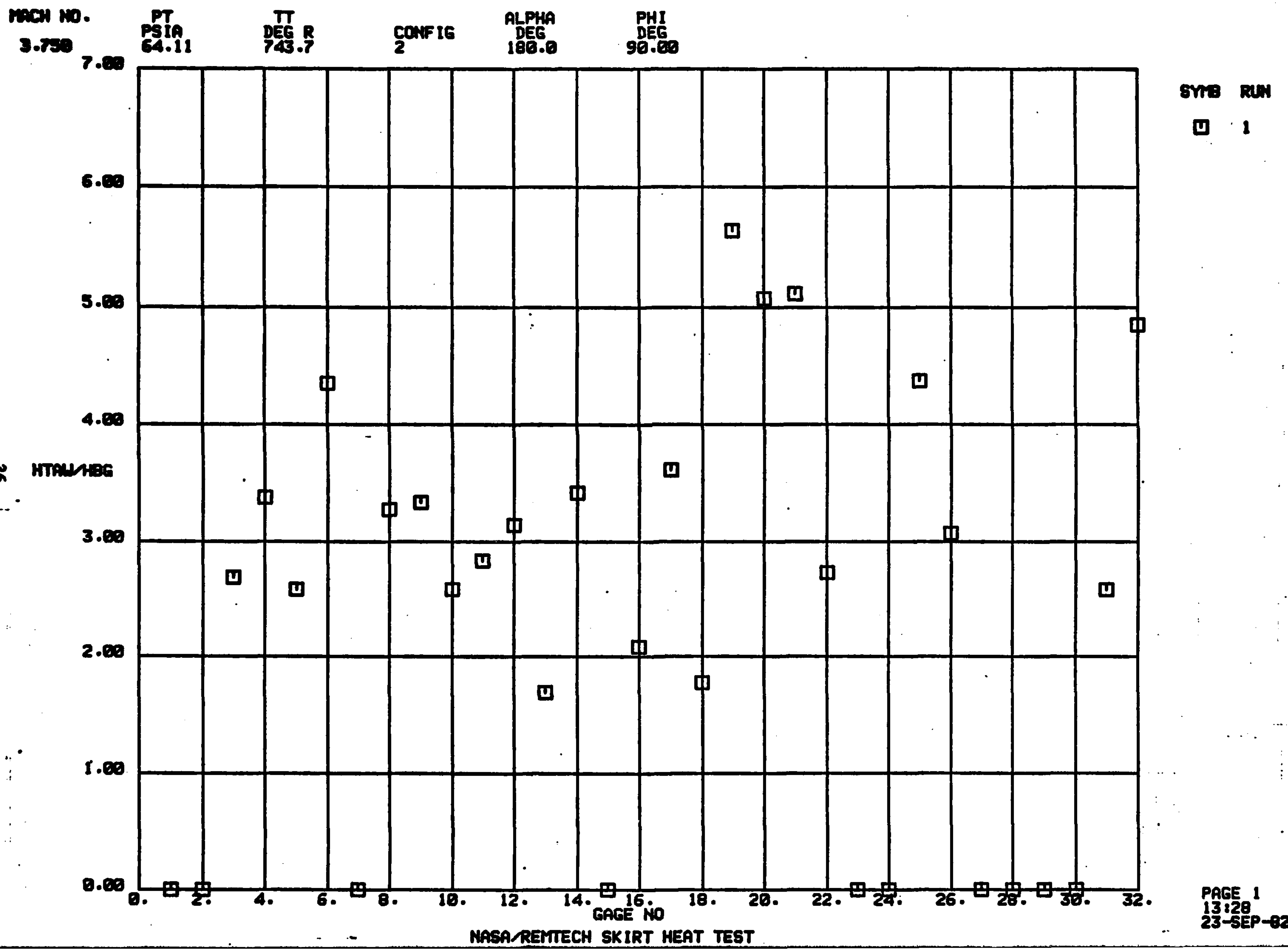
RUN	CONFIGURATION	MACH NUMBER	PT (PSIA)	TT (DEGR)	ALPHA (DEG)	ALPI (DEG)	ALPS1 (DEG)	ALPS2 (DEG)	PHI (DEG)
1	SHORT NOZZLE	3.75	64.11	743.7	180.0	-6.0	0.0	6.0	90.0

T (DEGR)	P (PSIA)	Q (PSIA)	V (FT/SEC)	RHO (LBM/FT3)	MU (LBF-SEC/FT2)	RE (FT-1)	H-DG (BTU/FT2-SEC-R)	PT2 (PSIA)	PSKT (PSIA)
195.1	5.925E-01	5.83	2567.5	8.199E-03	1.570E-07	4.168E+06	4.046E-03	1.101E+01	1.056E+01

TAP NUMBER	THB (DEG)	DEL (DEG)	PM (PSIA)	PM/PT2	(PT2-PM)/PT2
1	10.0	80.0	1.0407E+01	9.5281E-01	4.7194E-02
2	100.0	10.0	1.0355E+01	9.4086E-01	5.9137E-02
3	190.0	100.0	1.0577E+01	9.6100E-01	3.8999E-02
4	200.0	170.0	1.0834E+01	9.8436E-01	1.5641E-02
5	0.0	0.0	1.0929E+01	9.9300E-01	6.9972E-03

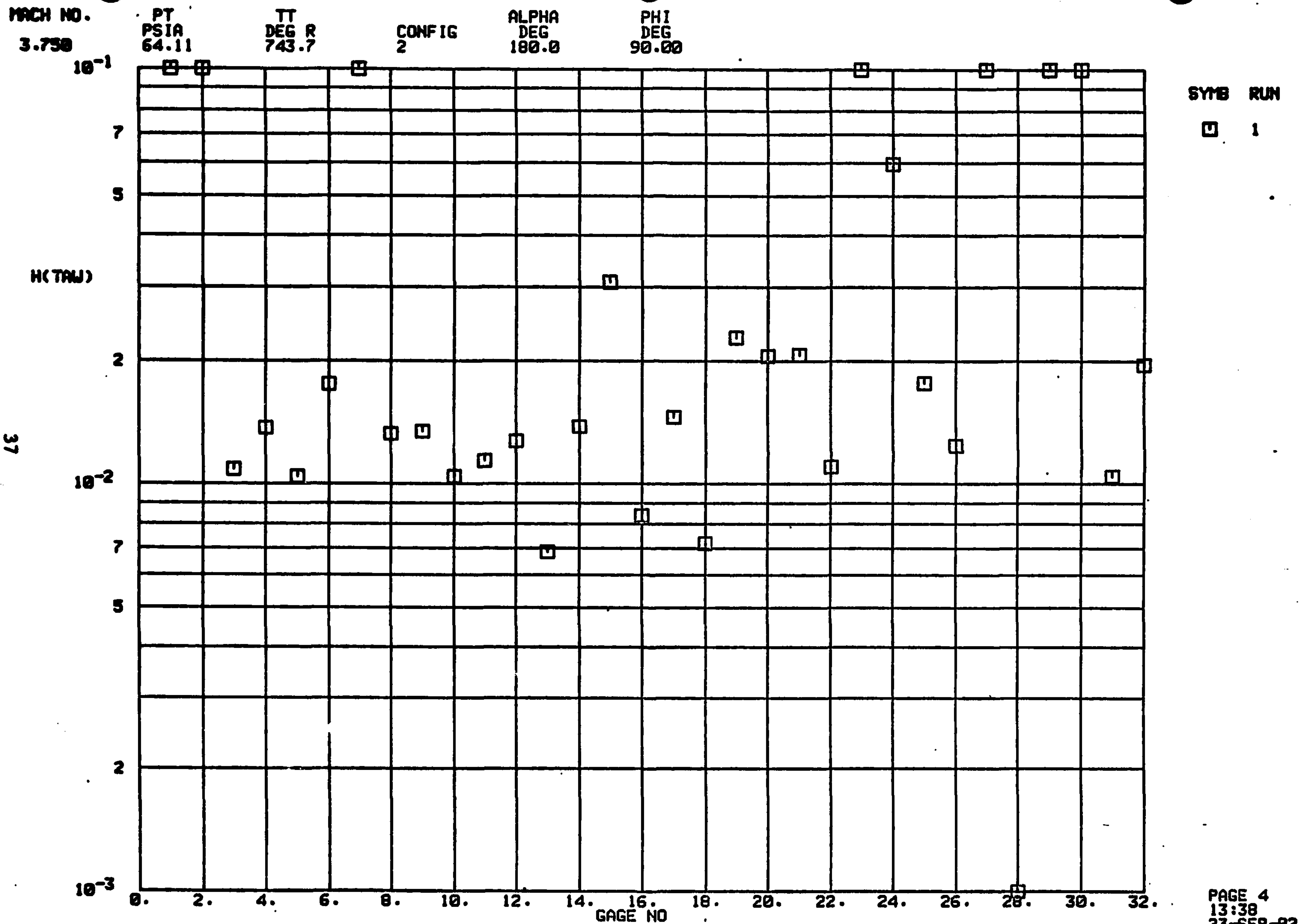
APPENDIX IV

SAMPLE PLOTTED DATA



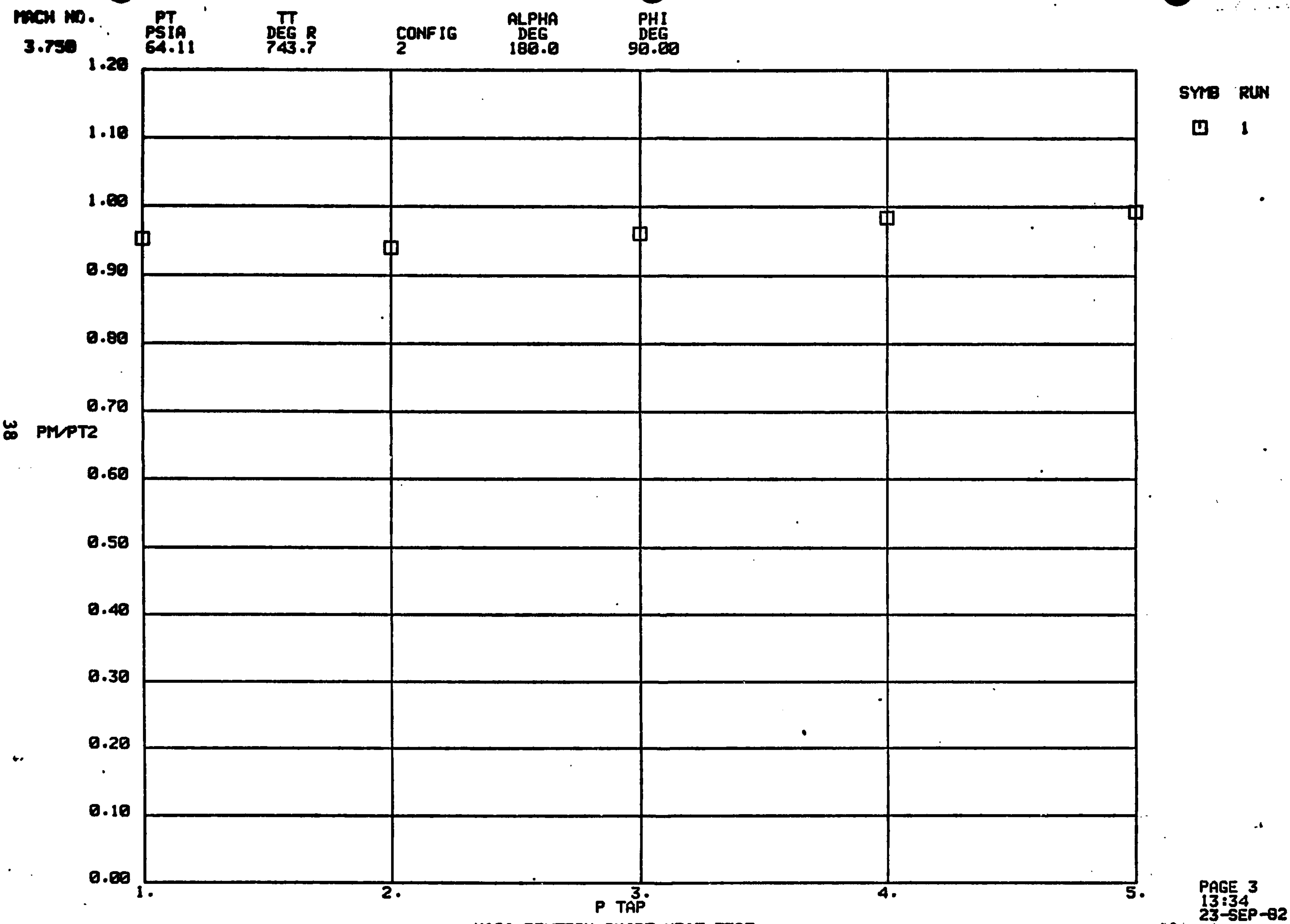
MACH NO.
3.750
PT
PSIA
64.11
TT
DEG R
743.7
CONFIG
2
ALPHA
DEG
180.0
PHI
DEG
90.00
SYMB RUN
1
HTAW/HBG
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0. 2. 4. 6. 8. 10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30. 32.
GAGE NO
NASA/REMTECH SKIRT HEAT TEST
PAGE 1
13:28
23-SEP-82

079



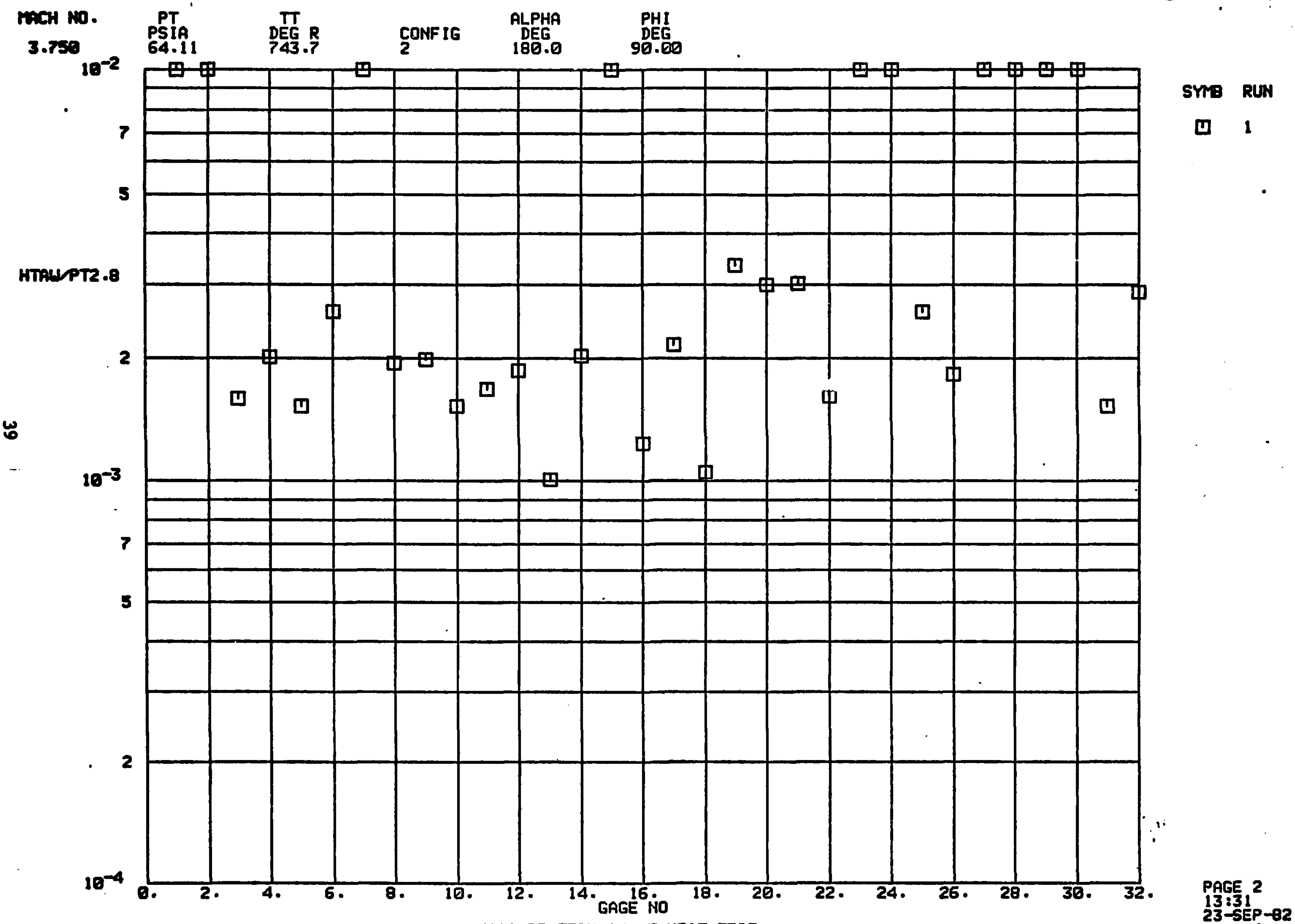
NASA/REMTECH SKIRT HEAT TEST

2. Heat-Transfer Coefficient



NASA/REMTECH SKIRT HEAT TEST

3. Nondimensional Pressure



NASA/REMTECH SKIRT HEAT TEST

APPENDIX V

THEORETICAL METHOD FOR COMPUTING LOCAL HEAT TRANSFER AND RECOVERY TEMPERATURE ON A YAWED CYLINDER

APPENDIX V

A theoretical method based on Ref. 2 was used to compute stagnation line heat-flux reference values (H-BG) for a yawed cylinder. This reference was calculated from the equation:

$$\text{H-BG} = 0.152 \left[\frac{\text{V sin(LAMDA)}}{\text{Mu-BG}}\right]^{0.6} \left[(\text{RHO*})(\text{Mu*})\right]^{0.8} \left[\text{DUDX}\right]^{0.2} \text{, BTU/ft}^2\text{-sec-°R} \quad (1)$$

where

$$\text{LAMDA} = |\text{ALPHA} - 90| \quad (2)$$

If ALPHA > 175; set LAMDA = 85 deg
If ALPHA < 95; set LAMDA = 5 deg

$$\text{DUDX} = 321.11 \left[\text{TE (1.0 - PRAT)}\right]^{0.5} \text{, 1/sec for cylinder of radius = 2.19 in.} \quad (3)$$

where:

$$\text{TE} = \text{TT} - \text{V}\left[\sin\text{(LAMDA)}\right]^{2} / 12012 \quad (4)$$

$$\text{MN} = \text{M cos (LAMDA)} \quad (5)$$

If MN $\geq$ 1

$$\text{PRAT} = (1.2\ \text{MN}^2)^{-3.5} \left[(7\ \text{MN}^2-1)/6\right]^{2.5} \quad (6)$$

$$\text{If MN} \leq 1\text{, PRAT} = \left(1 + \frac{\text{MN}^2}{5}\right)^{-3.5} \quad (7)$$

$$\text{RHO*} = 0.0838\ \text{P}/[(\text{T*})(\text{PRAT})] \quad (8)$$

$$\text{T*} = 264.75 + 0.38\ \text{TE} + 0.22\ (\text{TAW})_{\text{BG}}\text{, °R} \quad (9)$$

$$(\text{TAW})_{\text{BG}} = \text{T} + \left[\cos^2\text{(LAMDA)} + 0.897\sin^2\text{(LAMDA)}\right] \frac{\text{V}^2}{12012}\text{, °R} \quad (10)$$

$$\text{Mu-BG} = 7.30779 \frac{\text{TT}^{1.5}}{\text{TT} + 198.7} \times 10^{-7}\text{, slugs/ft-sec} \quad (11)$$

$$\text{Mu*} = 7.30779 \frac{\text{T*}^{1.5}}{\text{T*} + 198.7} \times 10^{-7}\text{, slugs/ft-sec} \quad (12)$$

NOTE: Beckwith-Gallagher equations supplied by REMTECH

3-8

DT